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EFFECTS OF WINDS ON THE STABILITY OF A THIN DISK

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ABSTRACT

Standard thin disk theory predicts that an inner disk region dominated by radiation pressure is thermally unstable. However, this kind of instability isn't detected in the observations of X-ray binaries. In this work, we revisit this issue by investigating the stability of a thin disk with magnetically driven winds. It is found that the disk winds can help to make a thin disk stable by taking away most of the energy released in the disk, resulting in a much cooler disk. The disk can always be stable even for a very weak initial field strength $\beta_{\rm p,0} \leq 400$ when $\alpha = 0.05$ and $B_\phi = 10B_{\rm p}$ are adopted.

Key words: accretion, accretion disks: instabilities: conference proceedings

1. INTRODUCTION

Standard thin disk theory has been extensively used in X-ray binaries and active galactic nuclei (AGNs) (Shakura & Sunyaev, 1973). However, the instability, appearing when the radiation pressure dominates in the inner disk region, isn't found in observations. For example, Gierliński & Done (2004) found that black hole X-ray binaries with luminosities ranging from 0.01 to 0.5 $L_{\rm Edd}$ are quite stable. So far, there are only two sources, GRS 1915+105 and IGR J17091-3624, which seem to possess the limit-cycle light curve predicted by the standard thin disk theory.

Two processes may help to change the theoretical results. First, a thin disk would be stable if its viscous stress were proportional to the gas pressure instead of the total pressure. However, MHD simulations suggest that the viscous torque should approximately scale with the total pressure. Secondly, the instability will disappear if the temperature of a thin disk decreases, which can reduce the relative importance of radiation pressure to the total pressure. We investigate the thermal stability of a thin disk with winds in this work, as disk winds can take away most of the gravitational energy released in the disk, thus helping to reduce the disk temperature and make the disk stable.

2. MODEL

We study a thin disk with magnetically driven winds surrounding a Kerr black hole.

When geometrical units $G = c = 1$ are adopted, the metric around a spinning black hole is

$$ds^2 = -\frac{R^2\Delta}{A}dt^2 + \frac{A}{R^2}(d\phi - \omega dt)^2 + \frac{R^2}{\Delta}dR^2 + dz^2, \quad (1)$$

$$\Delta = R^2 - 2MR + a^2,$$

$$A = R^4 + R^2a^2 + 2MRa^2,$$

$$\omega = \frac{2MaR}{A},$$

$$a = \frac{J}{M},$$

where M is the mass of the black hole, J and a are the angular momentum and specific angular momentum of the black hole, respectively, and ω is the dragging angular velocity of the metric.

The four basic equations (continuity, radial momentum, angular momentum and energy equation) of the thin disk are as follows:

$$\frac{d}{dr}(2\pi\Delta^{1/2}\Sigma v_{\rm r}) + 4\pi r\dot{m}_{\rm w} = 0, \quad (2)$$

$$\frac{\gamma_\phi AM}{r^4\Delta}\frac{(\Omega - \Omega_{\rm k}^+)(\Omega - \Omega_{\rm k}^-)}{\Omega_{\rm k}^+\Omega_{\rm k}^-} + g_{\rm m} = 0, \quad (3)$$

$$-\frac{\dot{M}}{2\pi}\frac{dL}{dr} + \frac{d}{dr}(rW_\phi^r) + T_{\rm m}r = 0, \quad (4)$$

$$\nu\Sigma\frac{\gamma_\phi^4 A^2}{r^6}\left(\frac{d\Omega}{dr}\right)^2 = \frac{16acT^4}{3\bar{\kappa}\Sigma}, \quad (5)$$

where the meanings of the parameters are the same as those of Li & Begelman (2014) (thereafter, LB14).

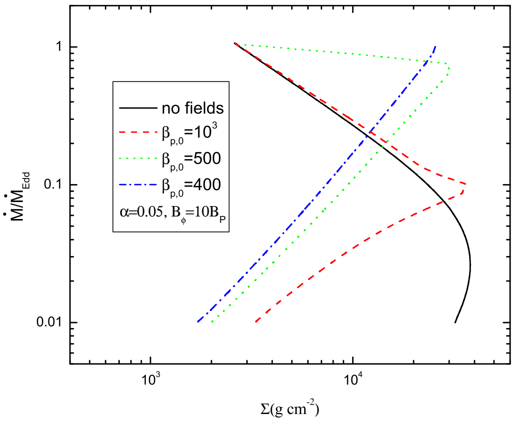

Figure 1. The $\dot{M}-\Sigma$ curve of a thin disk with winds at radius $R = 2R_{\rm ISCO}$, where $R_{\rm ISCO}$ is the innermost stable circular orbit.

3. RESULTS

We numerically solve equations (2) - (5) in this work. The numerical methods adopted are the same as LB14. In all the calculations, a conventional viscosity parameter $\alpha = 0.05$, black hole mass $m = M/M_\odot = 10$, spin $a = 0.9$ and magnetic field $B_\phi = 10B_{\rm p}$ are adopted, where B_ϕ and $B_{\rm p}$ are the toroidal and poloidal components of the field, respectively.

We study the stability of a thin disk in the $\dot{M} - \Sigma$ curve (see figure 1), where the transition point from positive to negative slope corresponds to the value of the critical mass accretion rate, $\dot{M}_{\rm crit}$. It is found that the critical mass accretion rate, corresponding to the thermal instability, is greatly improved with the presence of disk winds. The disk is always stable when a very weak initial field strength $\beta_{\rm p,0} \leq 400$ is adopted, where $\beta_{\rm p} = (P_{\rm gas} + P_{\rm rad})/(B_{\rm p}^2/8\pi)$.

4. SUMMARY AND DISCUSSION

The critical mass accretion rate, corresponding to the thermal instability, can be significantly improved for a thin disk with winds, as the disk winds can help to cool the disk. Thus, a thin disk with winds is much more stable than a standard thin disk.

However, as suggested in LB14, despite of the increase of $\dot{M}_{\rm crit}$, the luminosity doesn't increase with increasing $\dot{M}_{\rm crit}$ because the disk temperature is greatly decreased.

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